ADVANCES IN ELECTROACTIVE POLYMERS AS ARTIFICIAL MUSCLES

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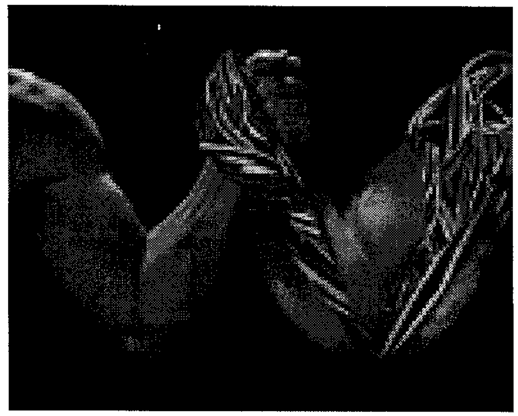
For many years, electroactive polymers (EAP) received relatively little attention due to the small number of available materials and their limited actuation capability. The recent emergence of EAP materials with large displacement response changed the potential capability and paradigms of these materials. The main attractive characteristic of EAP is their operational similarity to biological muscles, particularly their resilience and ability to induce large actuation strains. Even though the actuation force of existing EAP materials and their robustness require further improvement, there has already been a series of reported successes. The successful applications that were demonstrated include catheter steering element, miniature manipulator, dust-wiper, miniature robotic arm, and grippers. Some of the currently considered applications may be difficult to accomplish and it is important to scope the requirements to the level that current materials can address. Using EAP to replace existing actuators may be a difficult challenge and therefore it is highly desirable to identify a niche application where it would not need to compete with existing capabilities. The application of these materials as actuators to drive various manipulation, mobility and robotic devices involves multidiscipline including materials, chemistry, electro-mechanics, computers, electronics, etc. In this seminar the current efforts, recent advances and the expectations for the future will be reviewed.

BIOGRAPHY

Dr. Yoseph Bar-Cohen is a physicist specialized in ultrasonic NDE and electroactive materials and mechanisms. He received his Ph. D. in Physics (1979) and M.Sc. in Materials Science (1973) from the Hebrew University, Jerusalem, Israel. He is Senior Research Scientist, Group Leader and the Resident NDE Expert at the Jet Propulsion Laboratory responsible for the Nondestructive Evaluation and Advance Actuators (NDEAA) Technologies (http://ndeaa.jpl.nasa.gov/). NDEAA is a technology thrust of the JPL/Caltech's Mechanical and Robotics Technologies Group. Dr. Bar-Cohen is also an Adjunct Professor at the University of California, Los Angeles (UCLA) and a Fellow of the American Society for Nondestructive Testing (ASNT). Two notable discoveries of Dr. Bar-Cohen are the leaky Lamb waves (LLW) and polar backscattering phenomena in composite materials. In 1991, he established the NDEAA Lab that led to a series of innovative concepts and mechanisms, including an ultrasonic drill that is being considered for planetary exploration missions. Currently, he is responsible for developing electroactive polymer actuators, piezoelectric motors, piezoelectric pump, ultrasonic NDE methods, real time sensing, geophysical probing techniques, haptic interfaces, and high power ultrasonic techniques. His scientific and engineering accomplishments have earned him the 2001 NASA Honor Award: NASA Exceptional Engineering Achievement Medal and the 2001 SPIE's NDE Life Time Achievement Award.

Advances in Electroactive Polymers as Artificial Muscles



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Historical prospective

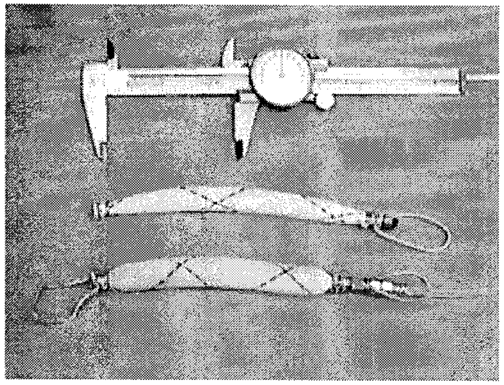
- Roentgen [1880] is credited for the first experiment with EAP electro-activating rubber-band to move a cantilever with mass attached to the free-end
- Sacerdote [1899] formulated the strain response of polymers to electric field activation
- Eguchi [1925] discovery of electrets* marks the first developed EAP
  - Obtained when carnauba wax, rosin and beeswax are solidified by cooling while subjected to DC bias field.
- Another important milestone is Kawai [1969] observation of a substantial piezoelectric activity in PVF2.
  - PVF2 films were applied as sensors, miniature actuators and speakers.
- Since the early 70's the list of new EAP materials has grown considerably, but the most progress was made after 1990.

* Electrets are dielectric materials that can store charges for long times and produce field variation in reaction to pressure.

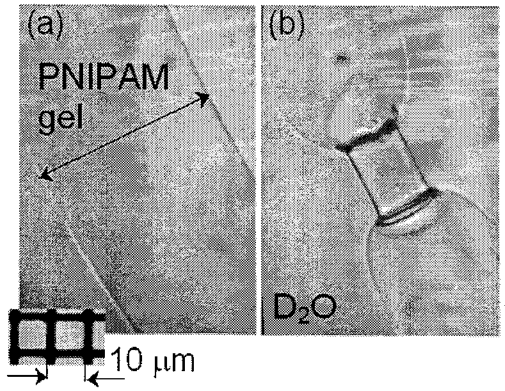
Non-Electro Active Polymers (NEAP)

- Conductive and Photonic Polymers
- Smart Structures and Materials
- Deformable Polymers
  - Chemically Activated
  - Shape Memory Polymers
  - Inflatable Structures
  - Light Activated Polymers
  - Magnetically Activated Polymers

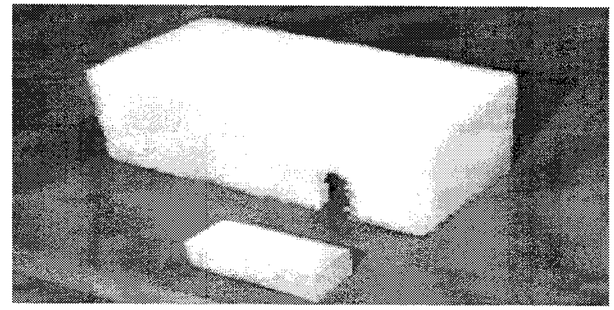
Non-Electric Activated Polymers (NEAP)



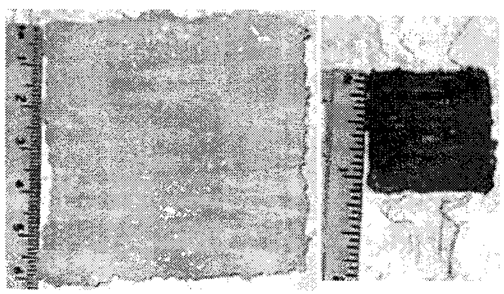
McKibben Artificial Muscles
Air Pressure activation
(Hannaford, B.U. Washington)



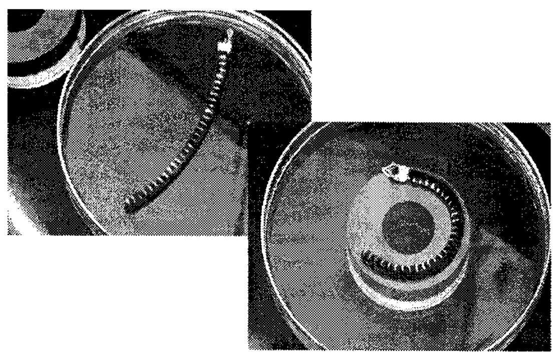
Laser Illuminated Polymer
Light activation (H. Misawa, Japan)



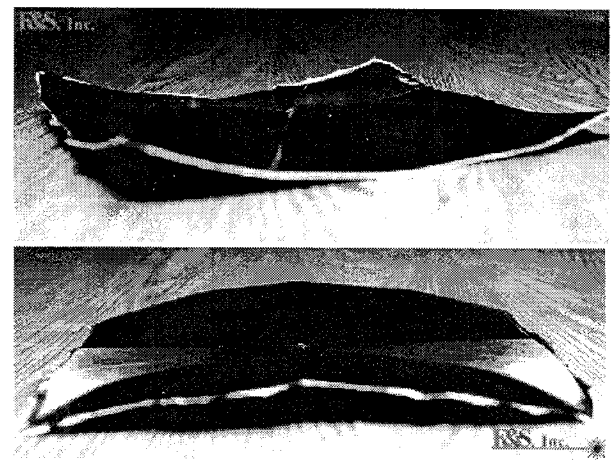
Shape Memory Polymers
Heat/pressure activation (W. Sokolowski, JPL)



Ionic Gel Polymers
Chemical transduction (P. Calvert, UA)



Ferrogel
Magnetic Activation (M. Zrinyi, Hungary)



Smart Structures
Polymers with Stable shapes
(S. Poland, Luna Innovations, VA)

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COMPARISON BETWEEN EAP AND WIDELY USED TRANSDUCING ACTUATORS

Property	EAP	EAC	SMA
Actuation strain	>10%	0.1 - 0.3 %	<8% short fatigue life
Force (MPa)	0.1 – 3	30-40	about 700
Reaction speed	μsec to sec	μsec to sec	sec to min
Density	1- 2.5 g/cc	6-8 g/cc	5 - 6 g/cc
Drive voltage	2-7V/ 10-100V/μm	50 - 800 V	NA
Consumed Power*	m-watts	watts	watts
Fracture toughness	resilient, elastic	fragile	elastic

* Note: Power values are compared for documented devices driven by such actuators.

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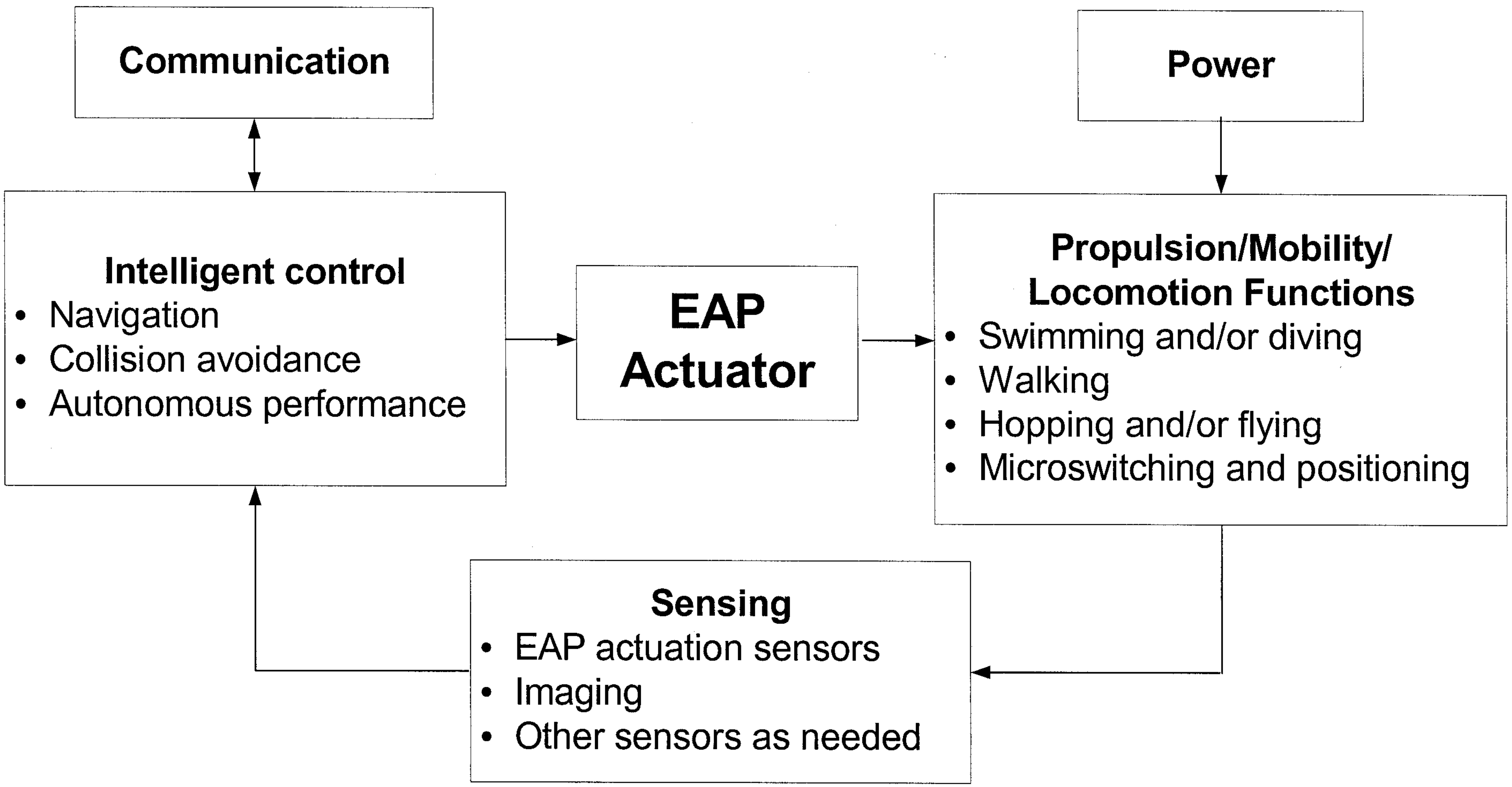
ELEMENTS OF AN EAP ACTUATED ROBOTS



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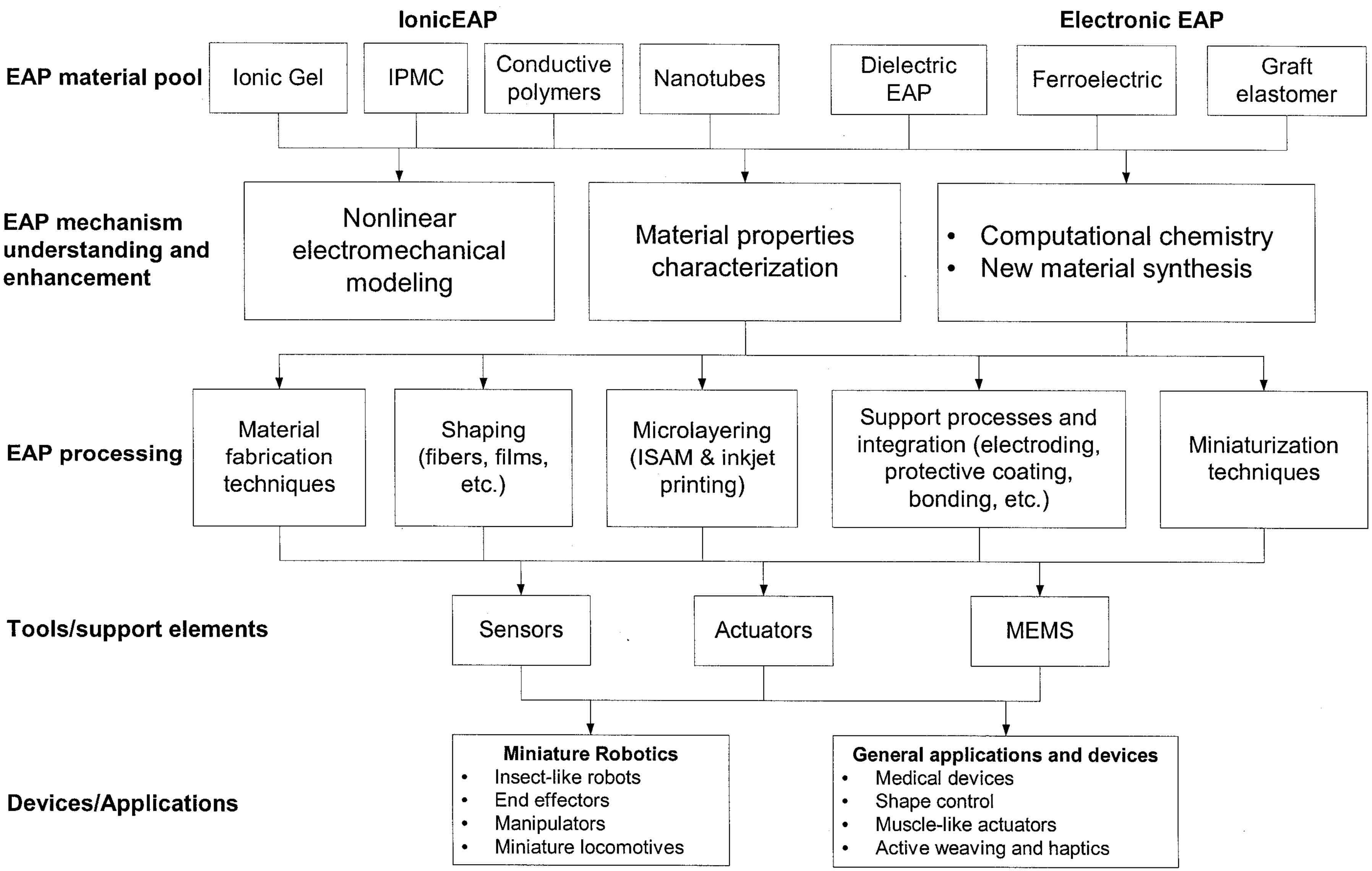
EAP infrastructure



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Electroactive Polymers (EAP)

ELECTRONIC EAP

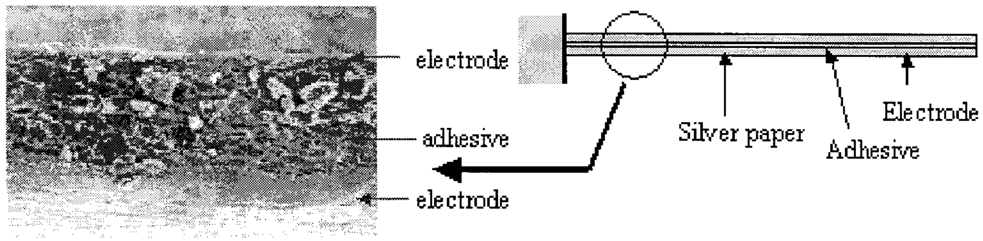
- Dielectric EAP
- Electrostrictive Graft Elastomers
- Electrostrictive Paper
- Electro-Viscoelastic Elastomers
- Ferroelectric Polymers
- Liquid Crystal Elastomers (LCE)

IONIC EAP

- Carbon Nanotubes (CNT)
- Conductive Polymers (CP)
- ElectroRheological Fluids (ERF)
- Ionic Polymer Gels (IPG)
- Ionic Polymer Metallic Composite (IPMC)

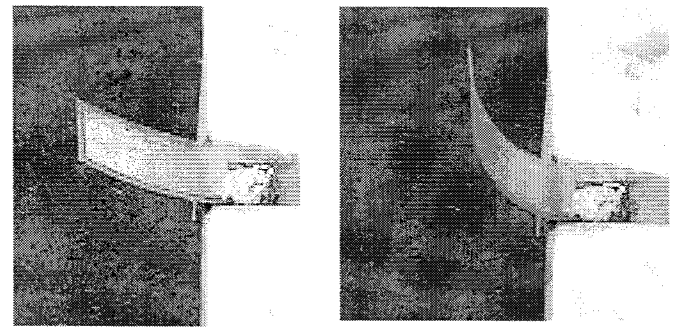
Electronic EAP

ELECTRIC FIELD OR COULOMB FORCES DRIVEN ACTUATORS



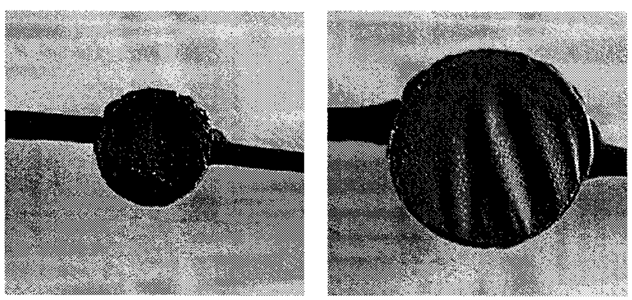
Paper EAP

[J. Kim, Inha University, Korea]



Ferroelectric

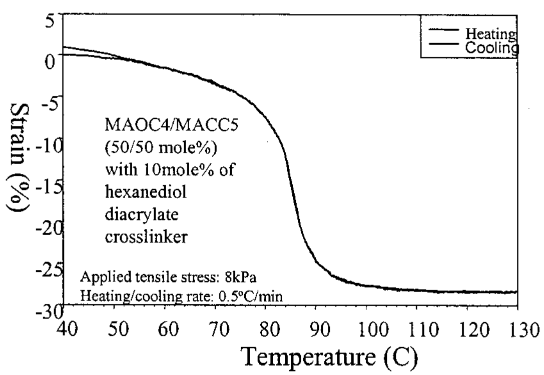
[Q. Zhang, Penn State U.]



Voltage Off **Voltage On**

Dielectric EAP

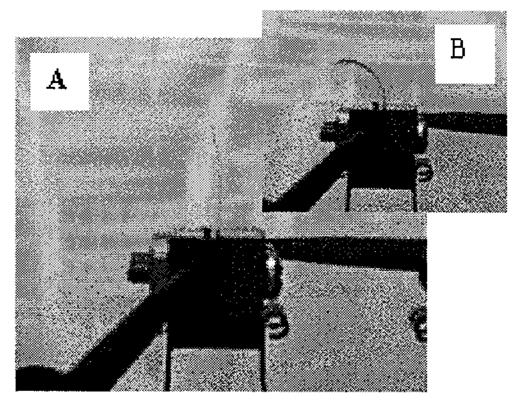
[R. Kornbluh, et al., SRI International]



Liquid crystals

(Piezoelectric and thermo-mechanic)

[B. R. Ratna, NRL]



Graft Elastomer

[J. Su, NASA LaRC]

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Electronic EAP

Actuator type	Principle	Advantages	Disadvantages	Reported Types
Ferroelectric Polymers	Polymers that exhibit noncentro-symmetric sustain shape change in response to electric field. Some of these polymers have spontaneous electric polarization making them ferroelectric. Recent introduction of electron radiation in P(VDF-TrFE) copolymer with defects in their crystalline structure dramatically increased the induced strain	• Induce relatively large strain (~5%). • Offer high mechanical energy density resulting from the relatively high elastic modulus • Permit AC switching with little generated heat • Rapid response (mSec levels)	• Require high voltage (~150 MV/m) • Applying radiation is expensive • Difficult to mass produce • Making thin multilayers is still a challenge.	Electron radiated P(VDF-TrFE)
Dielectric EAP or ESSP	Coulomb forces between the electrodes squeezes the material, causing it to expand in the plane of the electrodes. When the stiffness is low a thin film can be shown to stretch 200-380%.	• Large displacements reaching levels of 200-380% • Rapid response (mSec levels) • Inexpensive to produce	• Require high voltage (~150 MV/m) • Obtaining large displacements compromises the actuation force • Require pre-strain	• Silicone • Polyurethane
Electrostrictive Graft Elastomers	Electric field causes molecular alignment of the pendant group made of graft crystalline elastomers that are attached to the backbone.	• Strain levels of 5% • Relatively large force • Cheaper to produce • Rapid response (mSec levels)	• Require high voltage (~150 MV/m)	Copolymer – poly(vinylidenr fluoride-trifluoroethylene)
Liquid Crystal Elastomers	• Contract when heated • Exhibit spontaneous Ferroelectricity	• Induce large stress and strain (~ 200kPa and 45%, respectively)	• Slow response • Hysteresis	• Polyacrylate • polysiloxane

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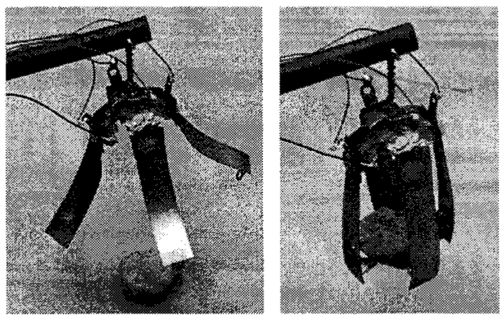
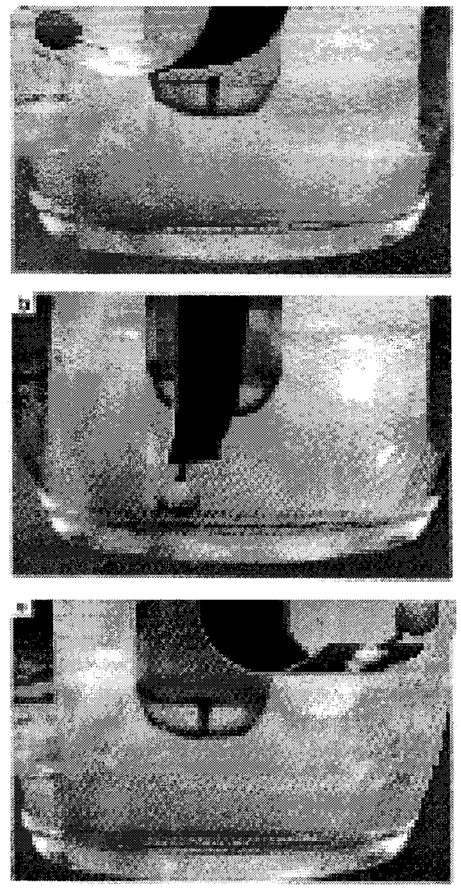
Ionic EAP

Turning chemistry to actuation



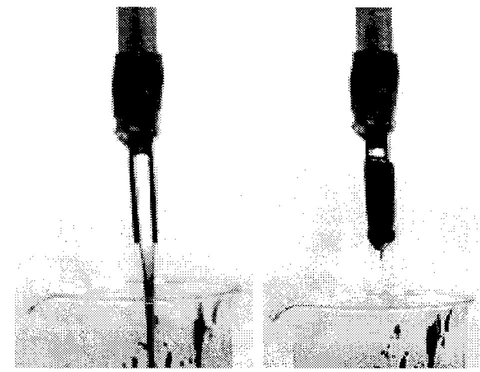
IPMC

[JPL using ONRI, Japan & UNM materials]



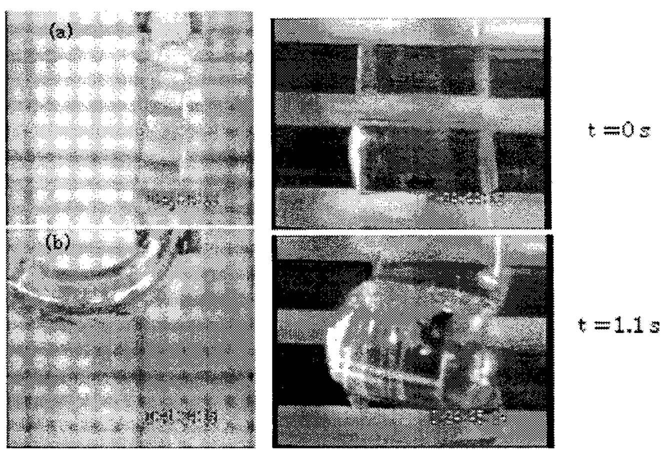
Conductive Polymer

[San Sebastian U., Spain, and JPL]



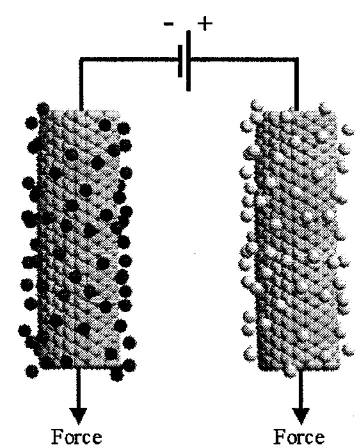
ElectroRheological Fluids (ERF)

[ER Fluids Developments Ltd]



Ionic Gel

[T. Hirai, Shinshu University, Japan]



Carbon-Nanotubes

[R. Baughman et al, Honeywell, et al]

Ionic EAP

Actuator type	Principle	Advantages	Disadvantages	Reported types
Ionic gels (IGL)	Application of voltage causes movement of hydrogen ions in or out of the gel. The effect is a simulation of the chemical analogue of reaction with acid and alkaline	Potentially capable of matching the force and energy density of biological muscles	Operate very slowly - it would require very thin layers and new type of electrodes to become practical	Poly(vinyl alcohol) gel with dimethyl sulfoxide, and polyacrylonitrile (PAN) with conductive fibers
Ion-Exchange Polymer Metal Composites (IPMC)	The base polymer provides channels for mobility of positive ions in a fixed network of negative ions on interconnected clusters. Electrostatic forces and mobile cation are responsible for the bending.	• Require low voltage (1-10 V) • Provide significant bending • Potentially self-sensing	• Low frequency response (effectively below 1-Hz) • Extremely sensitive to dehydration and developed coating is ineffective. • DC permanent deform it • Hydrolysis above 1.23V • Displacement drift	Base polymer: • Nafion® (perfluorosulfonate made by DuPont) • Flemion® (perfluorocaboxylate, made by Asahi Glass, Japan). **Cations**: tetra-n-butylammonium, Li+, and Na+ **Metal**: Pt and Gold
Conductive Polymers (CP)	Materials that swell in response to an applied voltage as a result of oxidation or reduction, depending on the polarity causing insertion or de-insertion of (possibly solvated) ions.	• Require relatively low voltage • Induce relatively large force • Extensive body of knowledge • Biologically compatible	• Need surface protection to operate in dry environment • Suffer fatigue after repeated activation of several Kcycles. • Slow response (<40-Hz)	Polypyrrole, Polyethylenedioxythiophene, Poly(p-phenylene vinylene)s, Polyaniline, and Polythiophenes.
Carbon Nanotubes (CNT)	The carbon-carbon bond of nanotubes (NT) suspended in an electrolyte changes length as a result of charge injection that affects the ionic charge balance between the NT and the electrolyte	• Potentially provide superior work/ cycle & mechanical stresses • Carbon offers high thermal stability at high temperatures <1000 °C	• Expensive • Difficult to mass produce	Single and multi-walled carbon nanotubes
Electrorheological fluids (ERF)	ERFs experience dramatic viscosity change when subjected to electric field causing induced dipole moment in the suspended particles to form chains along the field lines	• Viscosity control for virtual valves • Enable haptic mechanisms with high spatial resolution	• Requires high voltage	Polymer particles in fluorosilicone base oil

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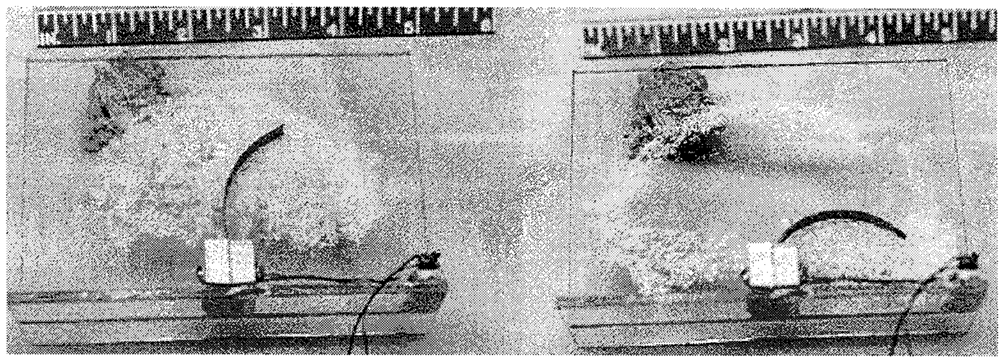
Current EAP
Advantages and disadvantages

EAP type	Advantages	Disadvantages
Electronic EAP	· Can operate in room conditions for a long time · Rapid response (mSec levels) · Can hold strain under DC activation · Induces relatively large actuation forces	· Requires high voltages (~150 MV/m) · Requires compromise between strain and stress · Glass transition temperature is inadequate for low temperature actuation tasks
Ionic EAP	· Large bending displacements · Provides mostly bending actuation (longitudinal mechanisms can be constructed) · Requires low voltage	· Except for CPs, ionic EAPs do not hold strain under DC voltage · Slow response (fraction of a second) · Bending EAPs induce a relatively low actuation force · Except for CPs, it is difficult to produce a consistent material (particularly IPMC) · In aqueous systems the material sustains hydrolysis at >1.23-V

Considered planetary applications

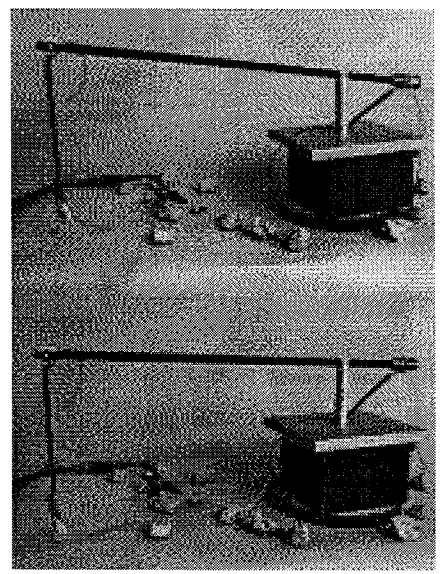
Dust wiper

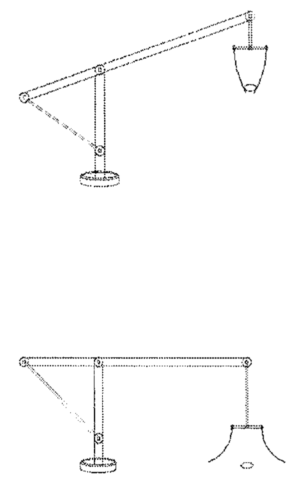
Bending EAP is used as a surface wiper



Sample handling robotics

Extending EAP lowers a robotic arm, while bending EAP fingers operate as a gripper





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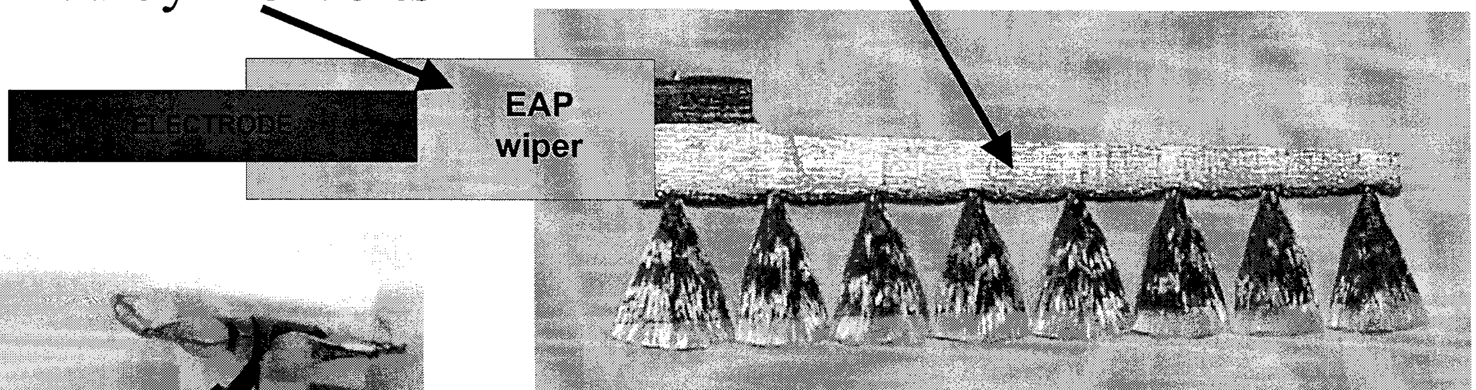
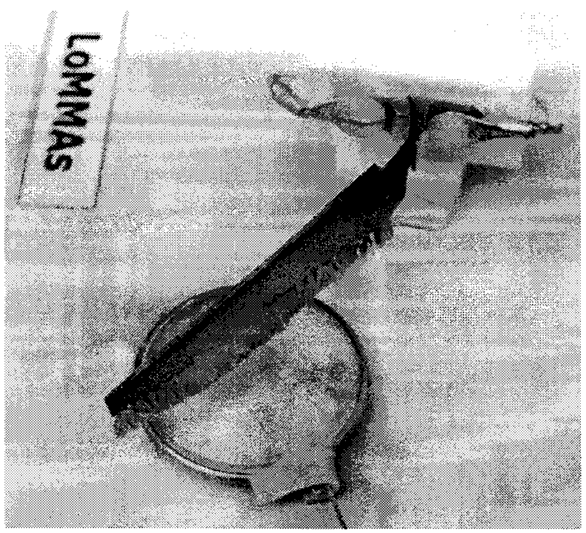
Surface wiper activated by EAP

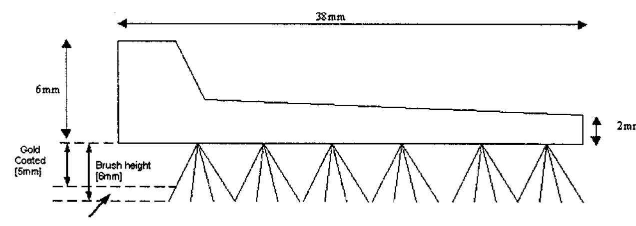
Actuated by 1-3 volts

Biased with 1-2KV for dust repulsion





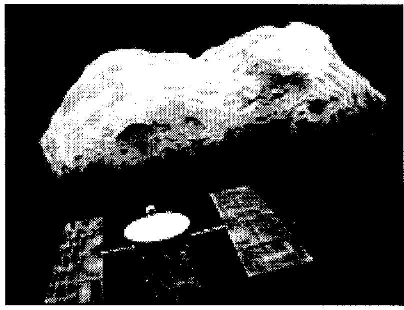
Graphite/Epoxy wiper blade* with fiberglass brush coated with gold



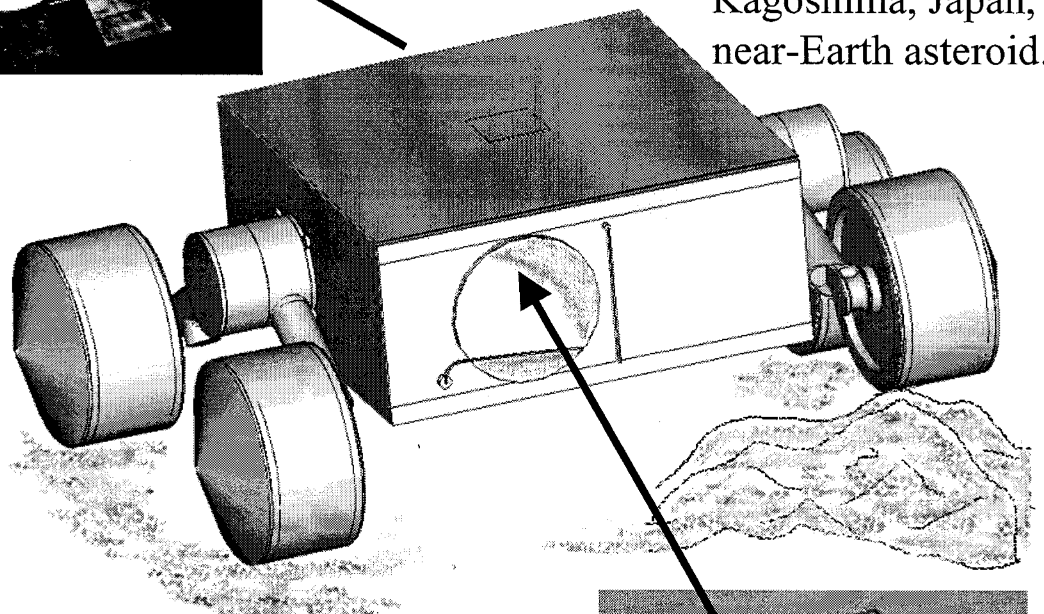
* Made by Energy Science Laboratories, Inc., San Diego, California

EAP Dust Wiper

for the MUSES-CN Nanorover



MUSES-CN mission was a joint NASA and NASDA (National Space Development Agency of Japan) mission scheduled for launch in January 2002, from Kagoshima, Japan, to explore the surface of a small near-Earth asteroid.



- An IPMC actuated wiper was selected as a baseline for the dust removal from the visual/IR window.
- The technical challenges were beyond the technology readiness requirements
- Due to budget constraints, this mission was cancelled in Nov. 2000.

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Challenges and solutions to the application of IPMC as bending actuators

Challenge	Potential Solution
Fluorinate base - difficult to bond	Etching the surface makes it amenable to bonding
Extremely sensitive to dehydration	Apply protective coating over the etched IPMC
Off-axis bending actuation	Constrain the free end and use a high ratio of length/width
Reverse bending drift under DC voltage	Limit the operation to cyclic activation to minimize this effect, and use cations such as Li^+ rather than Na^+.
Protective coating is permeable	Develop alternative coating, possibly using multiple layers
Electrolysis occurs at >1.23-V	Use efficient IPMC that requires low actuation voltage
Residual deformation particularly after intermittent activation	It occurs mostly after DC or pulse activation and it remains a challenge
Difficulties to assure material reproducibility	Still a challenge. May be overcome using mass production and protective coating.
Degradation with time due to loss of ions to the host liquid	Requires electrolyte with enriched cation content of the same species as in the IPMC

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Test Metric for EAP Properties

Measurement		Properties	Metric
Mechanical		Tensile strength [Pa]	Mechanical strength of the actuator material
		Stiffness [Pa]	Required to calculate blocking stress, mechanical energy density, and mechanical loss factor/bandwidth
		Coefficient of thermal expansion [ppm/C]	Affects the thermal compatibility and residual stress
Electrical		Dielectric breakdown strength [V]	Necessary to determine limits of safe operation
		Impedance spectra [ohms and phase angle]	Provides both resistance and capacitance data. Used to calculate the electrical energy density; electrical relaxation/dissipationand equivalent circuit.
		Nonlinear Current [A]	Used in the calculation of electrical energy density; quantify nonlinear responses/driving limitations
		Sheet Resistance [ohms per square]	Used for quality assurance
Microstructure Analysis		Thickness (electrode & EAP), internal structure, uniformity and anisotropy as well as identify defects.	These are features that will require establishing standards to assure the quality of the material
Electro-active Properties	Strain	Electrically induced strain [%] or displacement [cm]	Used in calculation of 'blocking stress' and mechanical energy density
	Stress	Electrically Induced Force [g], or Charge (C)	Electrically induced force/torque or Stress induced current density
	Stiffness	Stress/strain curve	Voltage controlled stiffness
Environmental Behavior		Operation at various temperatures, humidity and pressure conditions	Determine material limitations at various conditions

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EAP Properties

- Required drive voltage (V)
- Induced Stress (MPa)
- Induced Strain (%)
- Bandwidth (Hz) or response rate (sec)
- Power density (W/cm^3)
- Efficiency (%)
- Density (g/cm^3)
- Lifetime (cycles)
- Operating environment (Temperature, pressure, humidity, etc.)

Potential EAP applications

- EAPs offers unique characteristics to produce highly maneuverable, noiseless, agile biologically-inspired mechanisms.
- EAP can be used to provide actuators that require simple drive signals but their nonlinear behavior needs to be taken into account.
- The development and application of EAP materials and mechanisms involves interdisciplinary expertise in chemistry, materials science, electronics, mechanisms, computer science and others.
- Robustness and the limited actuation force are constraining the technology

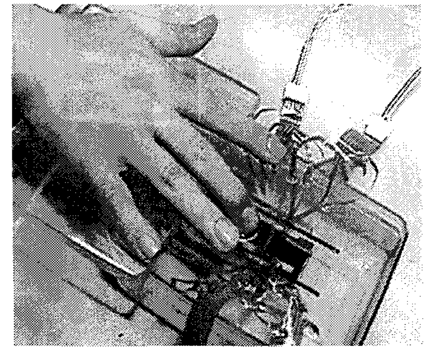
Applications

Underway, under consideration or being sought

- **Mechanisms**
  - Lenses with controlled configuration
  - Mechanical Lock
  - Noise reduction
  - Anti G-Suit
- **Robotics, Toys and Animatronics**
  - Biologically-inspired Robots
  - Toys and Animatronics
- **Human-Machine Interfaces**
  - Haptic interfaces
  - Tactile interfaces
  - Orientation indicator
  - Smart flight/diving Suits
  - Artificial Nose
  - Braille display
- **Planetary Applications**
  - Sensor cleaner/wiper
  - Shape control of gossamer structures
  - Dust wiper and particles sieve
- **Controlled Weaving**
  - Garment and Clothing
- **Medical Applications**
  - Biological Muscle Augmentation or Replacement
  - Miniature in-Vivo EAP Robots for Diagnostics and Microsurgery
  - Catheter Steering Mechanism
  - Tissues Growth Engineering
  - Interfacing Neuron to Electronic Devices Using EAP
  - Active Bandage
  - Electroactive Sock
- **Liquid and Gases Flow Control**
  - Pumps
  - Flight control surfaces/Jet flow control
- **MEMS and Nano-Technologies**
- **EM Polymer Sensors &Transducers**

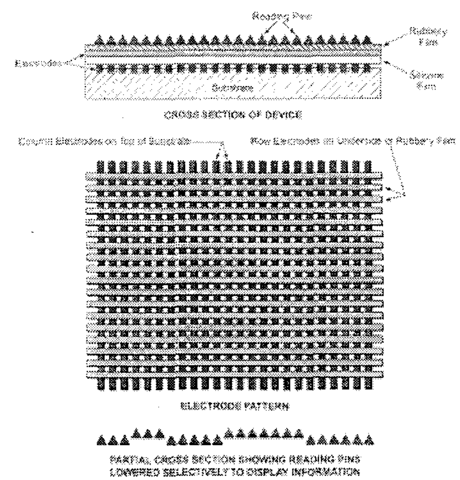
Human-Machine Interfaces

- Interfacing human and machine to complement or substitute our senses would enable important medical applications.
- Researchers at Duck U. connected electrodes to a brain of a money and were able to control a robotic arm. This breakthrough opens the possibility that the human brain would be able to operate prosthetics that are driven by EAP.
- Feedback is required to “feel” the environment around the artificial limbs. Currently, researchers are developing tactile sensors, haptic devices, and other interfaces.



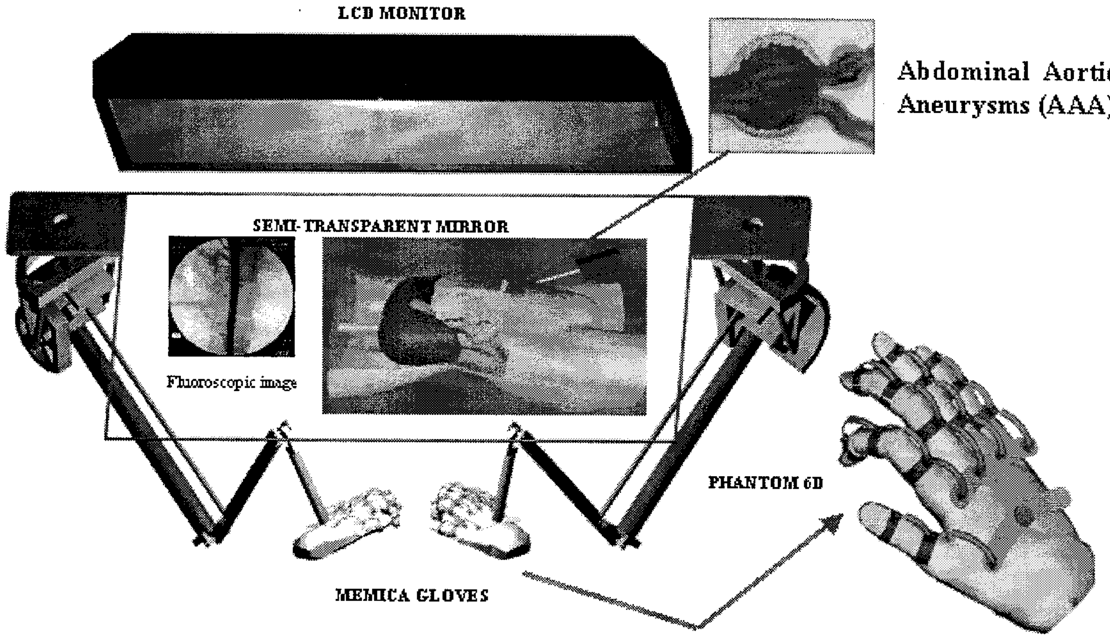
Tactile Interface

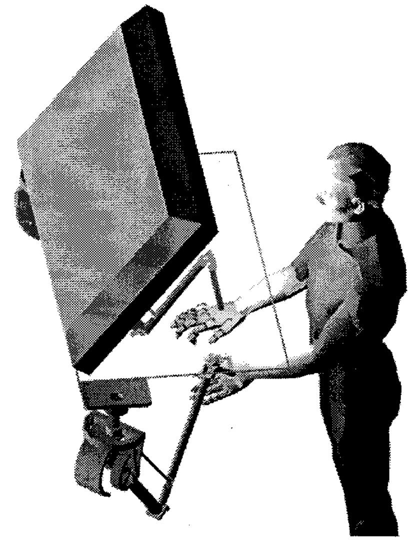
(S. Tadokoro, Kobe U., Japan)



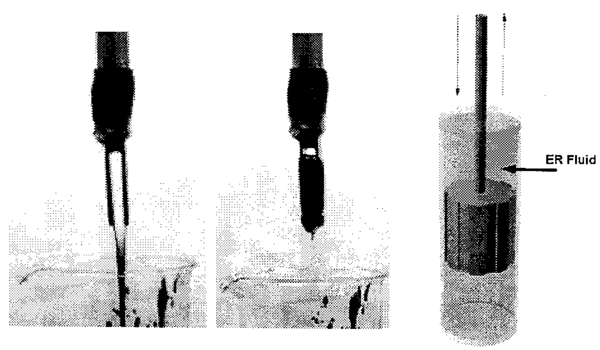
Active Braille Display

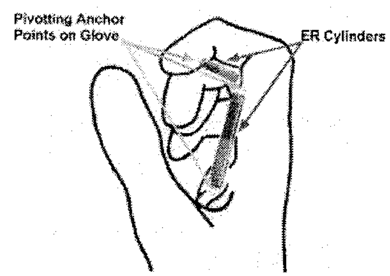
MEMICA (remote MEchanical MIrroring using Controlled stiffness and Actuators)

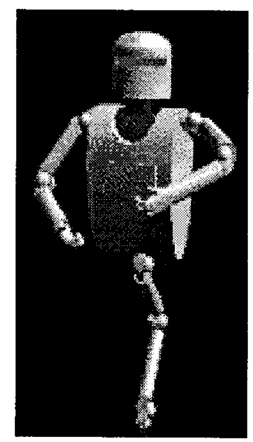




Electro-Rheological Fluid at reference (left) and activated states (right). [ER Fluid Developments Ltd, UK]







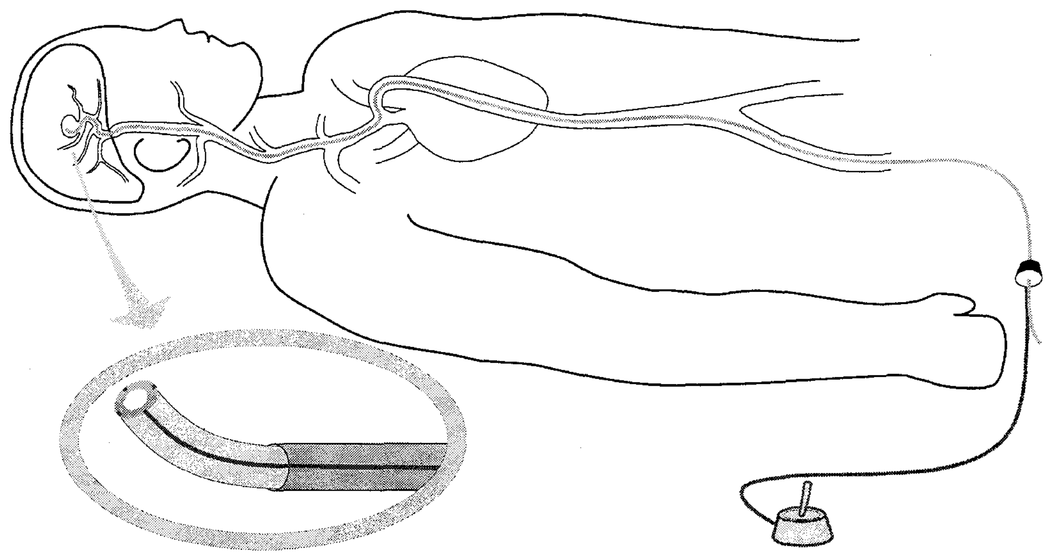
Y. Bar-Cohen, JPL, yosi@jpl.nasa.gov

Medical Applications

- EAP for Biological Muscle Augmentation or Replacement
- Miniature in-Vivo EAP Robots for Diagnostics and Microsurgery
- Catheter Steering Mechanism
- Tissues Growth Engineering
- Interfacing Neuron to Electronic Devices Using EAP
- Active Bandage

Catheter Guide Using IPMC

[K. Oguro, ONRI, Japan]



Human Face to EAP Applications

- Benign tumor damaged a nerve resulting absence of 'plantar reflex' in the left foot making Mr. Posoff walk with a limp.

- Mr. Posoff is seeking a walking assist device, possibly electroactive sock, that is not cumbersome, awkward and obvious

- An e-mail call was sent in Nov. 2000 and many responses were received (Advanced Bionics Corp., Bioflex Inc., Cybercable (France), JPL, Northwestern U., Penn State, USC, Risoe Center (Denmark), etc.)

- Based on the responses – no current capability is available.

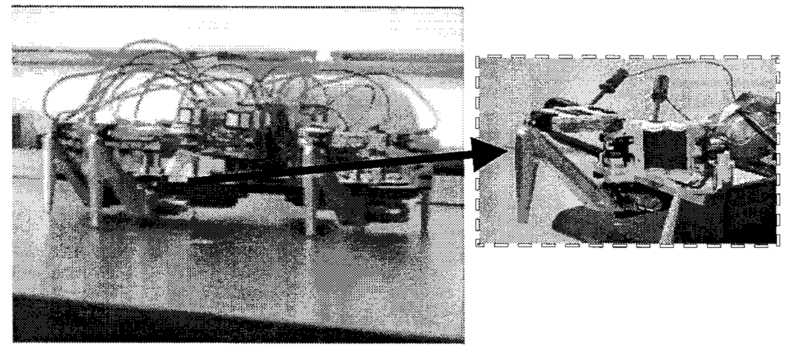
Challenge: Develop a smart robotic sock actuated by EAP that can work synchronically with the leg to eliminate the limp

Richard Posoff
richard.posoff@verizon.net

Robotics, Toys and Animatronics

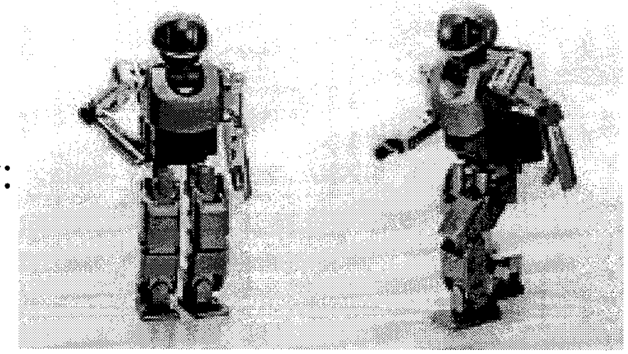
Biologically inspired robotics and rapid inexpensive mechanisms are highly attractive and offer novel possibilities that might be considered otherwise science fiction.

Android making facial expressions
(G. Pioggia et al. U. of Pisa, Italy)



Hexapod robot powered by dielectric EAP **(R. Kornbluh, et al., SRI International)**

Desired capability:



Sony's SDR3

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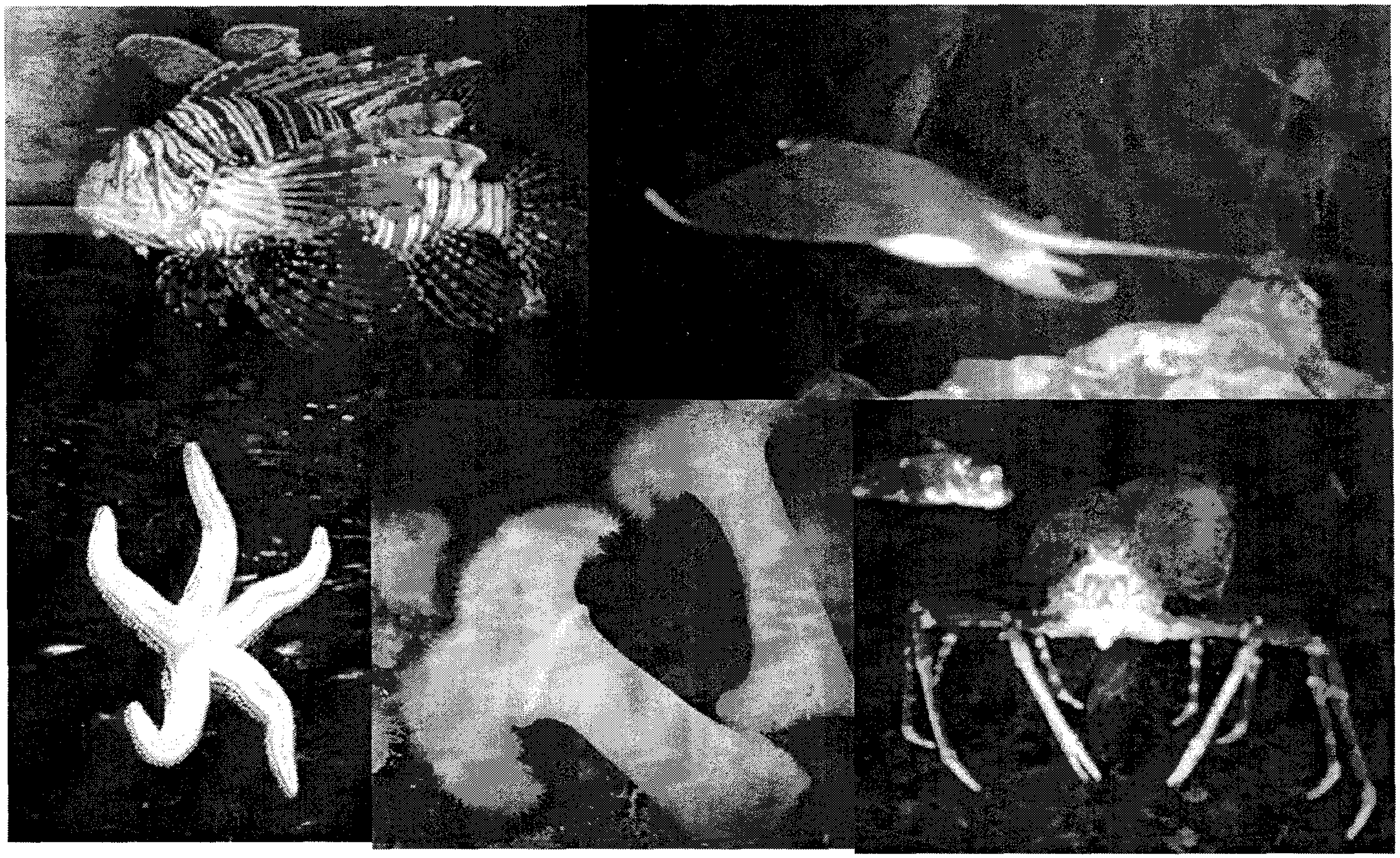
A challenge to EAP
Emulating sea creatures



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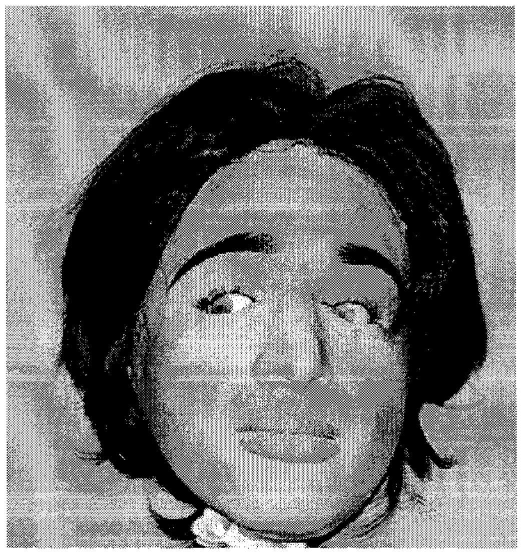
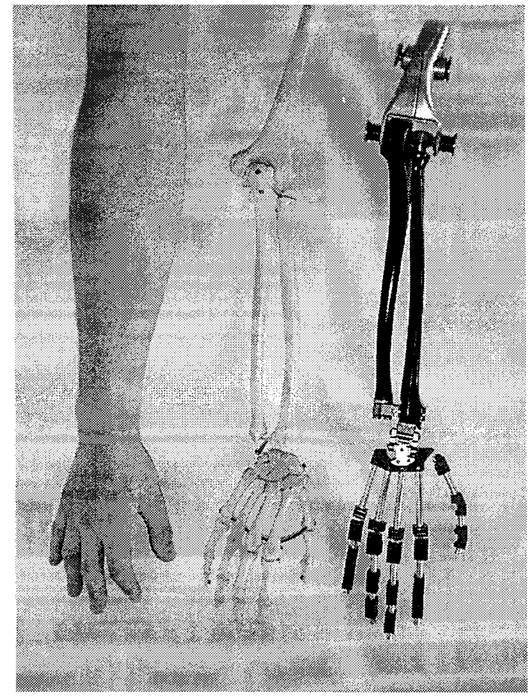
Platforms for EAP Implementation



Android making facial expressions

[G. Pioggia, et al, University of Pisa, Italy]



Platform for EAP

[G. Whiteley, Sheffield Hallam U., UK]

Micro-Electro-Mechanical Systems (MEMS)

- Making miniature devices
- Allow mass fabrication with repeatable performance
- Enable compact integration of comprehensive functionality combining "smart" sensors and actuators into a smart system.

Concerns and requirements

- No established database or standard test procedures
- Applications are needed where the specifications are within the EAP capability range
- Robustness – there are lifetime and reliability issues
- Scalability – it is not obvious how to make very large or very small EAP
- Competitiveness – there is a need for niche applications

International technical forums for interaction and collaboration

- SPIE Smart Structures and Materials Symposium - EAP Actuators and Devices Conference - held for the first time on March 1-2, 1999 in Newport Beach, CA

- MRS Conference - Symposium FF: Electroactive Polymers - held for the first time on Nov. 29 to Dec. 3, 1999 in Boston, MA

- In March 1999 - An EAP Actuators Worldwide webhub was formed with links to EAP R&D sites, general information and databases.
  http://ndeaa.jpl.nasa.gov/nasa-nde/lommas/eap/EAP-web.htm

- In June 1999, the first WW-EAP Newsletter issue was published electronically http//ndeaa.jpl.nasa.gov/nasa-nde/lommas/eap/WW-EAP-Newsletter.html

- In Nov. 1999 - An electronic communication platform (newsgroup) was formed. To register send eap-request@artemis.arc.nasa.gov "subscribe eap"

SUMMARY

- Electroactive Polymers have emerged as effective displacement actuators
- These materials offer the closest resemblance of biological muscle potentially enabling unique capabilities
- A series of new materials were developed and the infrastructure is being established to overcome the limitations of their current capability
- In recognition of the EAP limitation a series of international forums were established including conferences [SPIE (March) and MRS (Dec.)], Webhub, Newsletter, and Newsgroup.
- A challenge was posed to the EAP community to have an arm wrestling between robot that is equipped with EAP actuators and human.